

Light and heavy at the end of the funnel

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(Dated: September 10, 2010)

We show that, by taking a bare mass spectrum with constant spacings for the quark-antiquark propagators, which is subject to considerable mass shifts from meson loops, one adequately describes a large variety of mesonic resonances, from the light scalars to the $b\bar{b}$ states. All our results indicate that a harmonic-oscillator spectrum with universal frequency, in combination with coupled-channel effects, does a much better job than the $q\bar{q}$ spectrum of the funnel potential.

PACS numbers: 14.40.-n, 12.39.Pn, 11.80.Gw, 11.55.Ds

INTRODUCTION

For over three decades now, it has been widely assumed that the spectra of quarkonia can be described by a kind of *universal, funnel-type* potential [1], which basically stems from the naive picture of color-flux-tube formation at large interquark separations, while one-gluon exchange should represent the interactions at shorter distances. The Cornell potential [2] was the first and simplest version of such a potential. However, several mesonic resonances observed long ago, as well as some recently discovered ones, contradict such a description. In particular, the $\rho(1250-1300)$ (see e.g. Refs. [3–16]) does not at all fit in the $J^{PC} = 1^{--}$ isovector spectrum of, for instance, Ref. [17], which employed a semirelativistic version of a funnel-type confining $q\bar{q}$ potential. Moreover, evidence for the new vector charmonium resonances $\psi(5S)(4790)$ and $\psi(4D)(4870)$ [18–20], and also for an $\Upsilon(4S)(10735)$ [21], hints at masses that are again far from those predicted by the confining funnel potential. The same discrepancy between predictions of the funnel potential and experiment is observed e.g. for the firmly established $K^*(1410)$ [22], as well as the $f_2(1565)$ [22]. Note that the discrepancies here are not of a few tens of MeV, but rather of the order of 200 MeV!

Furthermore, the funnel potential does not accommodate the light scalar mesons $f_0(600)$, $K_0(800)$, $f_0(980)$, and $a_0(980)$, nor the heavy-light scalar $D_{s0}(2317)$, nor the $D_{s1}(2460)$ and the $D_{sJ}^*(2860)$, at least not without unitarization [23]. But instead of unitarizing one's favorite quark model, it has become fashion to fall back upon tetraquarks, meson molecules, hybrids, or glueballs, whenever a state does not fit the funnel potential [24, 25].

A better alternative to funnel confinement has been suggested three decades ago [26]. Based on the Weyl conformal invariance [27] property of the theory of quark dynamics (QCD), which leads, by a judicious choice of the time parameter, to anti-De Sitter confinement (AdS) [28], one obtains a harmonic-oscillator (HO) spectrum for $q\bar{q}$ systems [29]. The experimentally observed spectrum

is reproduced via the inclusion of meson loops [26, 30]. Most remarkably, in the lowest-order approximation to AdS, one obtains an interquark potential consisting of a Coulomb-like term and a linear term [31], exactly as in the case of lattice QCD (LQCD). Nevertheless, full AdS yields an HO-like spectrum. So it seems the lowest-order term of LQCD does not dictate the spectrum of the $q\bar{q}$ propagator, as it does not provide a satisfactory description of how confinement should follow from full QCD.

HARMONIC OSCILLATOR AND MESON LOOPS

Unitarization of the quark model also reveals threshold enhancements in electron-positron annihilation [32], which may explain e.g. why the $\psi(3770)$ consists of two structures [33], namely a $D\bar{D}$ threshold enhancement, interfering with a $c\bar{c}$ resonance [19]. Furthermore, this phenomenon explains the enhancement at 4.634 GeV observed by the Belle Collaboration in $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$ [34], not as a resonance, but rather a threshold enhancement [19], or to be more precise, at least three interfering threshold enhancements, namely $\Lambda_c^+\Lambda_c^-$, $D_{s1}(2536)^\pm D_s^{*\mp}$, and $D_{s0}(2317)^+ D_{s0}(2317)^-$. Further threshold enhancements are observed in data published by the BABAR Collaboration [35], though not as peaked structures, but rather as valleys due to depletion of the $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ signal at the opening of open-charm thresholds. Moreover, at the positions of $c\bar{c}$ resonances, one also observes dips in the data where peaks should be expected [35], most noticeably at the $\psi(4S)$ resonance (see Fig. 1 of Ref. [36]). Assuming depletion as an explanation for the $e^+e^- \rightarrow J/\psi\pi\pi$, $e^+e^- \rightarrow J/\psi KK$, and $e^+e^- \rightarrow \psi(2S)\pi\pi$ signals, one is led to consider the corresponding new “resonances” $X(4260)$, $X(4660)$, ... leftovers from open-charm decay [36]. Hence, the well-established $J^{PC} = 1^{--}$ $c\bar{c}$ spectrum anno 2010 still only consists of J/ψ , $\psi(2S, 3S, 4S)$, and $\psi(1D, 2D)$.

Harmonic-oscillator confinement, with a radial level

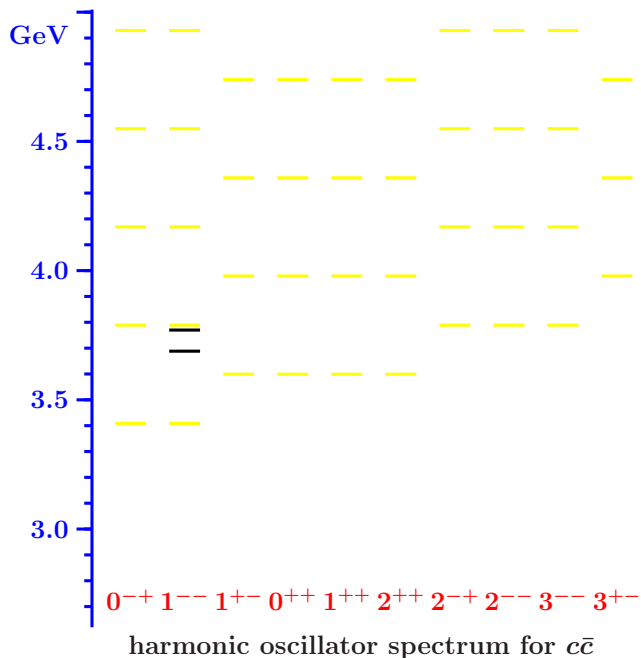


FIG. 1. Charmonium level spectrum (—) as obtained from the HO, for $m_c = 1.562$, $\omega = 0.190$ GeV. The two black dashes indicate where the central masses for the $\psi(2S)$ (lower dash) and the $\psi(1D)$ (upper dash) end up through the effect of meson loops. Similar mass shifts occur for other resonances and bound states.

splitting of 380 MeV, leads to abundantly many states of the $q\bar{q}$ propagator. This is shown for $c\bar{c}$ in Fig. 1. For other flavor combinations, the level scheme is exactly the same, just shifted up/down according to the sum of the effective quark masses. In Fig. 1, we depict the effect of meson loops on the central mass positions of the $\psi(2S)$ and the $\psi(1D)$. In the HO spectrum these two states are degenerate. However, due to the interaction generated by the meson loops, the poles associated with the resonances repel each other in such a way that one of them is subject to a small mass shift, whereas the other shifts considerably and downwards. Higher up in the $c\bar{c}$ spectrum, the mass shift of the lower pole becomes of the order of 150–200 MeV [26]. As a consequence, the associated resonance acquires a central mass which is very similar to that of the P states. Observing and disentangling such states is not exactly an easy task, as the past three decades have shown.

A way out is to study a well-isolated system, with just one set of quantum numbers, like vector $c\bar{c}$, which can be produced in e^+e^- annihilation. However, with a radial level separation of about 380 MeV for the S and D states, combined with expected widths of the order of 50–100 MeV, one needs a lot of good data, binned in intervals of 5 MeV at most. Furthermore, the opening of numerous thresholds complicates such a task even more. As a consequence, studying the lower part of the spectrum is

not the most adequate way to unravel the characteristics of quark confinement, since in particular the ground states suffer most from the coupling to open charm, while sharp open-charm thresholds give rise to noticeable enhancements. What one really needs are the higher radial excitations, very carefully distinguished from other effects, like, e.g., threshold enhancements. The latter occur less distinctly at higher energies, because they involve open-charm mesons have larger widths, so that thresholds are smeared out over several tens of MeV. Finally, the phenomenon of threshold enhancements also shows that specific open-charm channels decrease rapidly in amplitude for higher invariant masses [19]. Hence, studying the vector $c\bar{c}$ resonances in open charm leads to an extremely small set of data at higher energies. Nevertheless, although the quality of $e^+e^- \rightarrow c\bar{c}$ data is low for massive resonances, it is certainly justified to inspect such data carefully, in order to find signs of further resonances. Unfortunately, in practice lots of precious and, moreover, costly data are simply discarded in many analyses, by assuming an arbitrary background shape (see *e.g.* Fig. 3 of Ref. [38]). Three decades of very expensive accelerator physics without any further results in the $c\bar{c}$ vector spectrum is, to say the least, very embarrassing.

In Refs. [18–20, 36, 39–41] we have pointed at hints for the $\psi(3D)$, $\psi(5S)$, $\psi(4D)$, $\psi(6S)$, and $\psi(5D)$ $c\bar{c}$ resonances in several sets of reasonably good experimental data. Furthermore, we have found the first indications [18] of the $\psi(7S)$, $\psi(6D)$, and $\psi(8S)$ resonances in recent data on $e^+e^- \rightarrow D^*\bar{D}^*$, published by the BABAR Collaboration [42]. The resulting tentative spectrum of charmonium is shown in Fig. 2. It confirms the prediction of the model of Ref. [30], which is based on HO confinement and meson loops, a model denoted by us as HORSE.

In Fig. 2 we have indicated the prediction of the funnel-potential model of Ref. [37]. The data of Fig. 2 appear to contradict, in particular, the spin-orbit splittings as predicted in Ref. [37]. In the latter model, the S - D splittings for vector $c\bar{c}$ states become smaller for higher radial excitations, being only about 20 MeV for the $6D$ - $7S$ mass difference. From Fig. 2 we estimate this splitting to be roughly five to ten times larger. Now, in the HORSE, S - D mass differences are exactly zero at the quenched level, but get generated by meson loops. For the corresponding couplings, the three-meson vertices determined in Ref. [43] are employed, which involve the orbital and spin quantum numbers, not only of the $c\bar{c}$ pair, but also of the mesons in the loops. The resulting S - D splittings come out very different then, apart from the fact that the physical vector charmonium resonances naturally appear as mixtures of S and D states. We find that the combination dominated by the D wave shifts at most a few tens of MeVs away from the corresponding bare level. The dominantly S -wave combination shifts substantially more, viz. some 100–200 MeV, depending on the precise

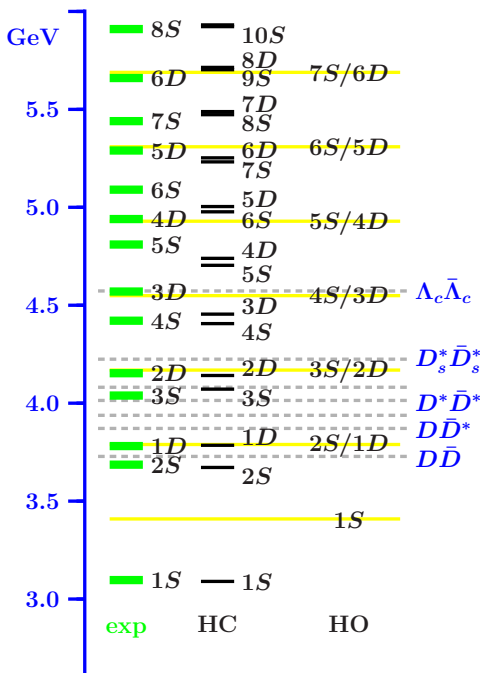


FIG. 2. $J^{PC} = 1^{--}$ $c\bar{c}$ level spectrum observed by us in data from experiment (exp) (■), as predicted by the funnel-type $c\bar{c}$ potential model of Ref. [37] (HC) (■), and as predicted by pure HO confinement (HO) (■). Meson and baryon loops shift the D states a few MeV down/up, whereas the S states shift 100–200 MeV downwards. For completeness, we also indicate the levels of the sharp, low-lying meson-meson and baryon-baryon thresholds (---) of the channels $D\bar{D}$, $D\bar{D}^*$, $D_s\bar{D}_s$, $D_s^*\bar{D}_s^*$, $D_s^*\bar{D}_s$, $D_s\bar{D}_s^*$, and $\Lambda_c^+\bar{\Lambda}_c^-$.

locations of nearby thresholds. This pattern is, to some extent, systematically repeated for higher radial excitations, which the present data seem to confirm.

For the light-quark spectrum the situation is even more complicated, as nonstrange and strange $q\bar{q}$ combinations have comparable spectra, which will come out on top of each other, besides possibly significant mixing of isoscalar $n\bar{n}$ ($n = u, d$) and $s\bar{s}$ states. To make things worse, decay channels involving kaons are common to both $n\bar{n}$ and $s\bar{s}$ resonances. The only system with a sufficient number of established states to find evidence (see Table 3 of Ref. [44]) for an HO level splitting of 380 MeV is given by the radially excited f_2 mesons. Moreover, the listing of experimental observations and/or published analyses of the data in the Particle Data Group (PDG) [22] tables is not very helpful in the light-meson sector. For example, whereas the HORSE clearly predicts the $\rho(2S)$ central mass at about 1.27 GeV, the $\rho(1250\text{--}1300)$ not even has its own entry. Observations of a ρ -type resonance at 1.25–1.3 GeV [8], which was moreover confirmed in a recent multichannel analysis [16], are listed under the $\rho(1450)$, with the “justification”:

Several observations on the $\omega\pi$ system in the 1200-MeV region may be interpreted in terms

of either $J^P = 1^-$ $\rho(770) \rightarrow \omega\pi$ production, or $J^P = 1^+$ $b_1(1235)$ production. We argue that no special entry for a $\rho(1250)$ is needed. The LASS amplitude analysis showing evidence for $\rho(1270)$ [12] is preliminary and needs confirmation. For completeness, the relevant observations are listed under the $\rho(1450)$.

The resulting confusion is confirmed in Ref. [45], where the authors, using dispersion relations, fail to observe the $\rho(1270)$ resonance in data from Refs. [46–48]. Even more absurd is the lumping of $\phi(1500)$ and $\phi(1900)$ observations under the $\phi(1680)$ [22].

Finally, besides the resonance poles that follow directly from $q\bar{q}$ confinement, meson loops may give also rise to dynamically generated resonances, of which the low-lying scalar mesons $f_0(600)$, $K_0(800)$, $f_0(980)$, and $a_0(980)$ were the first to be discovered [23]. But also the heavy-light scalar $D_{s0}(2317)$ is an example of such a type of resonance. Their existence will further complicate the classification of experimentally observed resonances. However, they can be studied and predicted by using the coupling of HO confinement to the relevant meson-meson and possibly baryon-baryon channels [49].

CONCLUSION

We have argued that the $c\bar{c}$ spectrum provides the best source to infer the confinement mechanism, which then also allows to understand and classify the spectra of other flavor combinations. The available data clearly suggest that HO confinement, complemented with meson loops, is the best candidate.

ACKNOWLEDGMENTS

One of us (EvB) wishes to thank the organizers of *Menu 2010* for their warm hospitality, and for bringing together many different views on the strong interactions. This work was supported by the *Fundação para a Ciência e a Tecnologia* of the *Ministério da Ciência, Tecnologia e Ensino Superior* of Portugal, under contract CERN/FP/109307/2009.

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